Models in the Design and Validation of Eddy Current Inspection for Cracking in the Shuttle Reaction Control System Thruster

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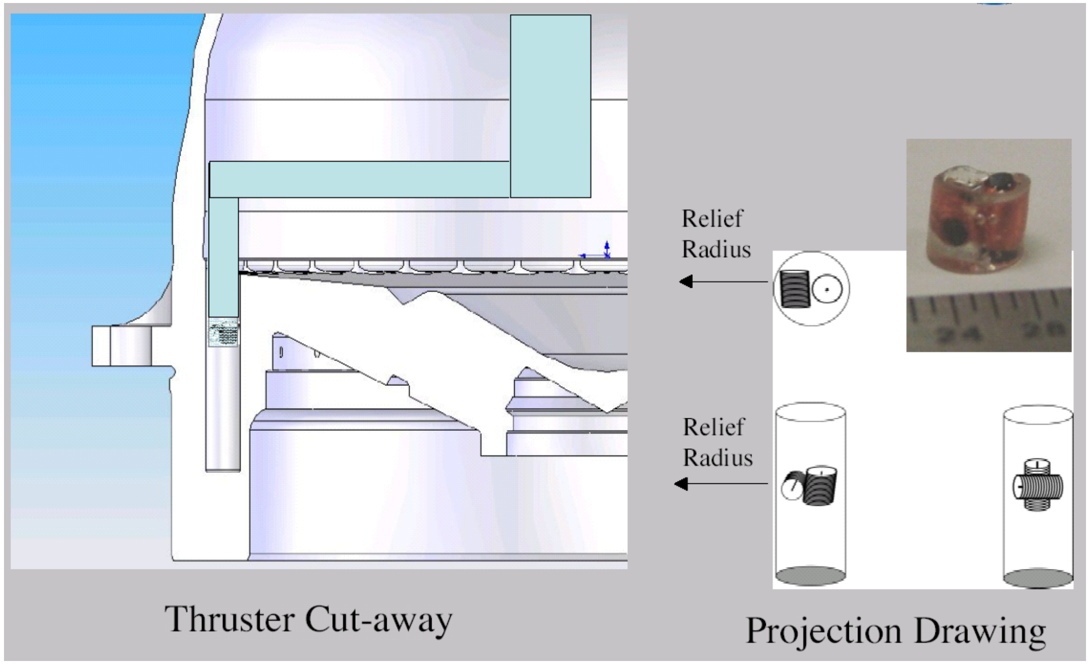
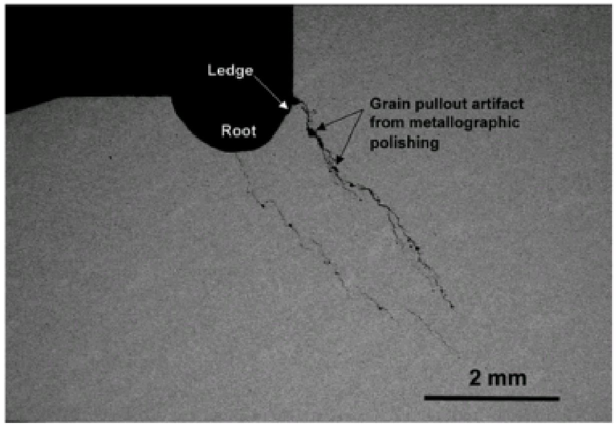
Outline

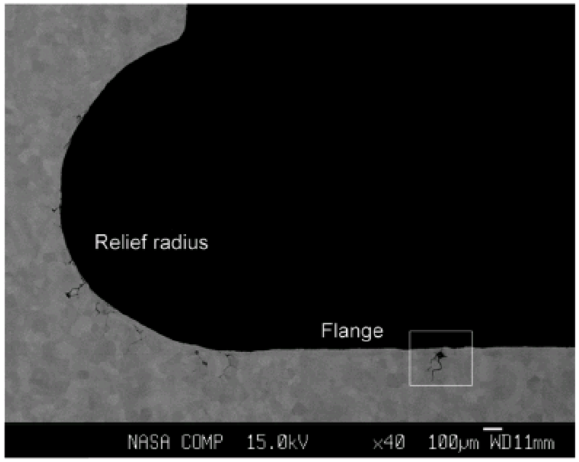
- Background – RCS Thruster
- Modeling Approach
- Results
  - FEM (Opera-3D®)
  - Volume Integral Method (VIC-3D®)
  - Design Trends
- Model-assisted POD Evaluation
  - Protocol
  - Preliminary Results
- Summary and Future Work

Background – RCS Thruster Problem



Thruster Cut-away
Projection Drawing





Observations for PRCS Thruster Inspection for Model:

- Cracks may emanate from relief radius or up flange. (*initially model from relief radius.*)
- Cracks are intergranular but generally open. (*initially model as open cracks.*)
- Projected crack depth (a) and ligament distance (a') more critical to measure than actual crack depth.

1. R. A. MacKay, S. W. Smith, S. R. Shah, R. S. Piascik, "Reaction control system thruster cracking consultation: NASA Engineering and Safety Center (NESC) Materials Super Problem Resolution Team (SPRT) Findings, NASA/TP—2005-214053.
2. B. Wincheski, "Eddy current techniques for nondestructive evaluation of complex materials and structures", NASA-Industry Partnership Workshop, Nondestructive Evaluation Sciences, June 20, 2006. Web site: www.industrynasapartnership.com/NASApresentations/Wincheski_Eddy_Current.pdf.

Background – Thruster Problem Model

Key Design Parameters:

A. **Part Geometry** — Thruster (cut-away, use simplified geometry)

B. **Part Material Properties** — Niobium alloy (Grain noise, Roughness of cavity)

C. **Crack Parameters**

Crack length	**0.000" – 0.175" (in terms of projected crack depth)**
Desired detection range	**0.020" – 0.060" (in terms of remaining material)**
Crack width	open / intergranular cracks
Crack orientation (angle)	30^{o} – 60^{o} (between hole)

Objectives for Case Study Problem:

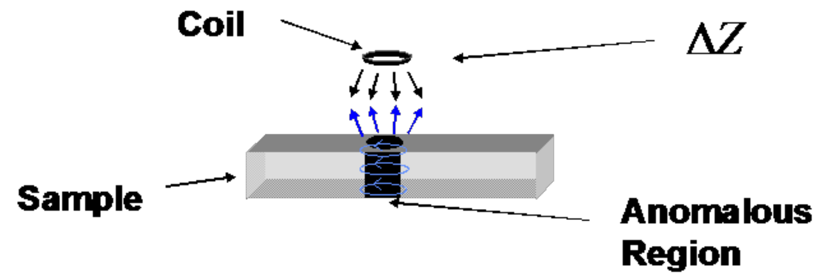
1. **Apply Models to Optimize Inspection Design**

Probe number:	**single or differential probes (location)**
Probe orientation:	**three different axial orientations with cavity**
Frequency (multiple):	**1.0 kHz – 50 kHz**
Probe (coil) dimensions:	(constrained by hole diameter)

2. **Explore Model-assisted POD Evaluation for NDE Technique Validation**

Eddy Current NDE Modeling

- **Formulation**



  - Maxwell's Equations

$$\nabla \times \vec{E} = -j\omega\vec{B}$$

$$\nabla \times \vec{H} = j\omega\vec{D} + J^{(e)}$$

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \cdot \vec{D} = \rho$$

= electric field
= magnetic field
= electric displacement
= charge density
$\vec{A}$ = magnetic vector potential
$\vec{J}_0$ = applied current density
μ = magnetic permeability
σ = electrical conductivity

  - Magnetic Vector Potential Definition

$$\nabla \times \vec{A} = \vec{B}$$

  - Isotropic, Linear, Inhomogeneous Medium

$$\nabla^2 \vec{A} = \mu \vec{J}_0 + \mu\sigma \frac{\partial \vec{A}}{\partial t} + \mu \nabla (1/\mu) \times (\nabla \times \vec{A})$$

  - Coil impedance calculation $Z = \dfrac{j\omega \int A \cdot ds}{I}$

3. C.V. Dodd and W. E. Deeds, "Analytical Solutions to Eddy-Current Probe-Coil Problems," Journal of Applied Physics, 1968

Numerical Methods

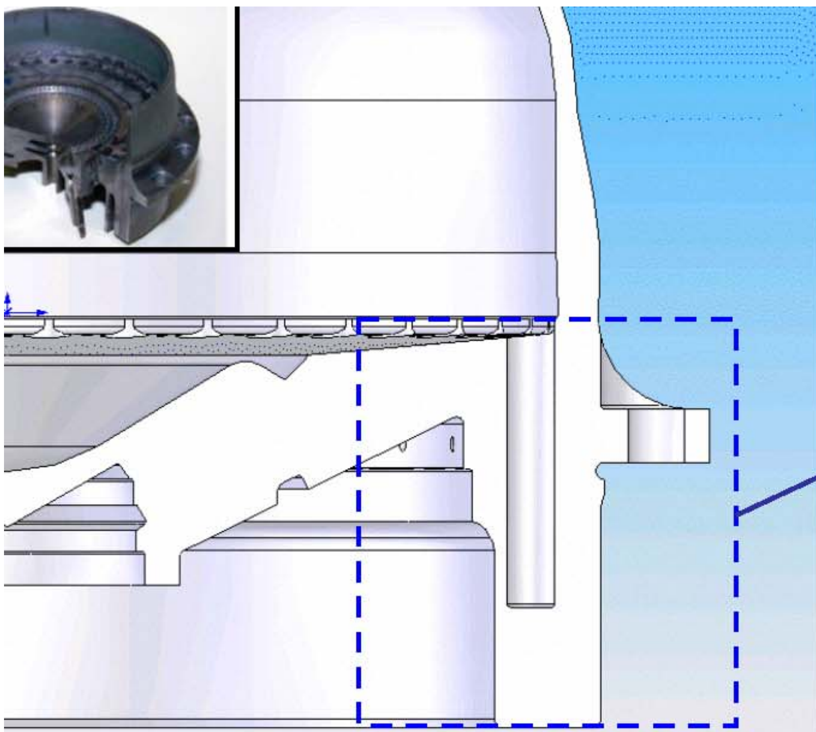
Methods:

- Analytical – TREE (truncated region eignefunction expansion)
- Finite Difference Method (FDM)
- Finite Element Method (FEM) [OPERA-3D, COMSOL]
- Boundary Integral Equation Method (BIEM) [ECSIM]
- Volume Integral Method (VIM) [VIC-3D]
- Meshless Methods

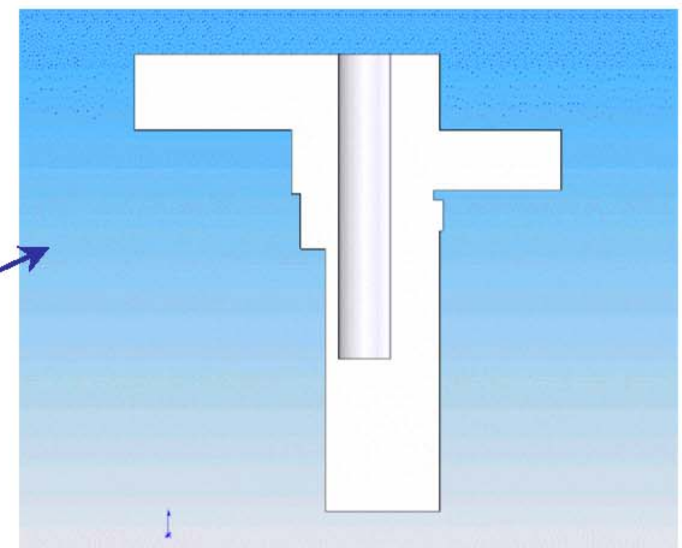
Advantages:

- **Finite Element Method (Opera 3D)**
  - Efficient discretization of awkward geometries
  - Calculations available anywhere within solution domain
- **Volume Integral Method (VIC-3D)**
  - Only region of the scatterer need be discretized
  - Fast

Thruster Problem Model



Thruster Cut-away

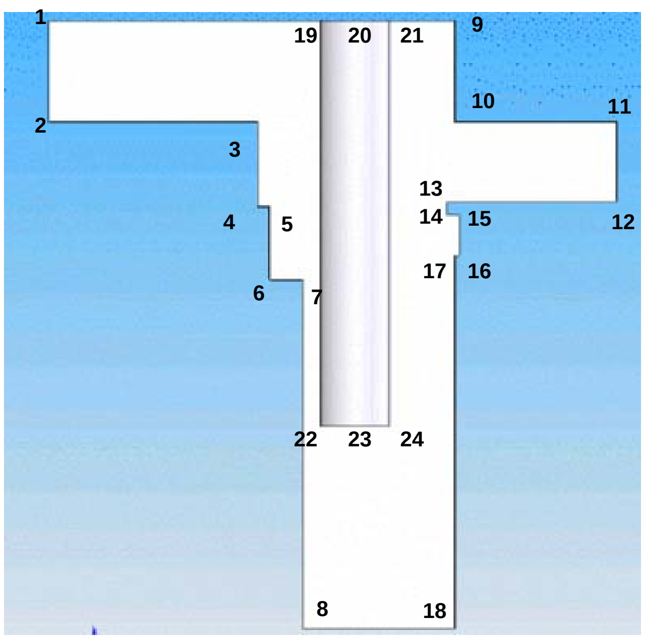


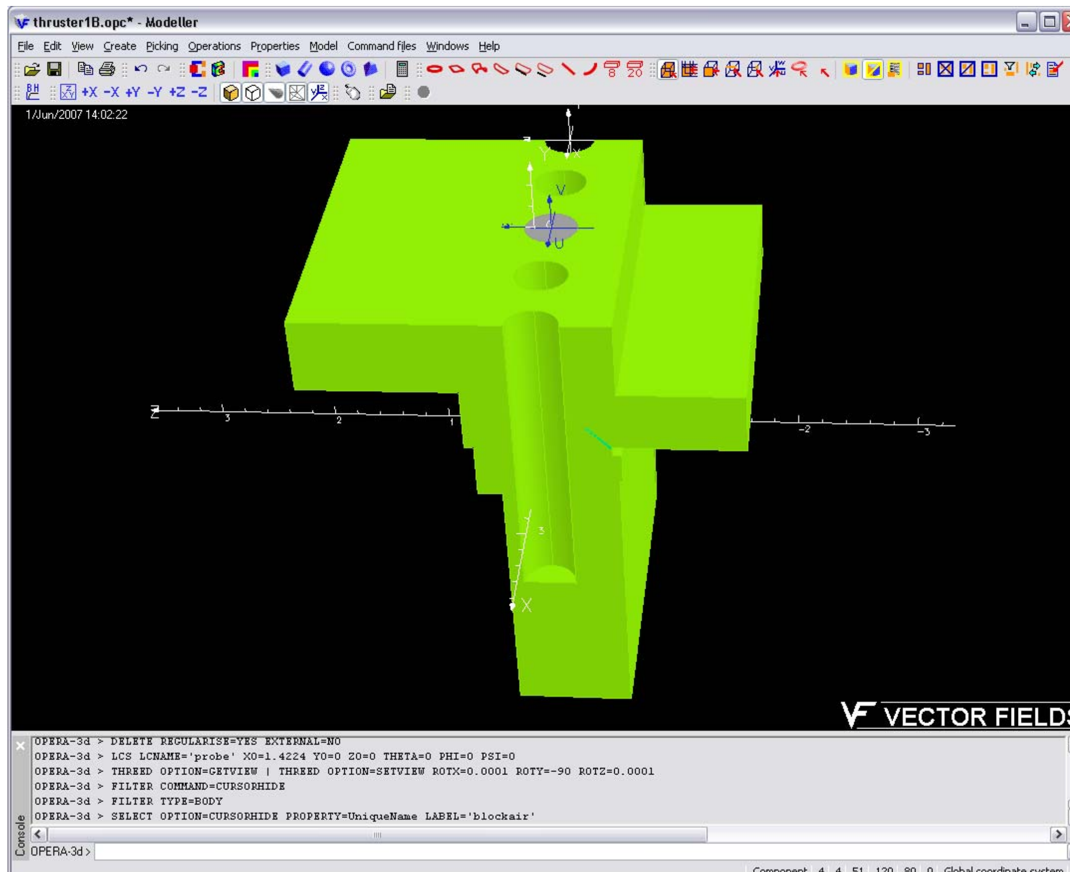
Simplified geometry for thruster model

Model – FEM (Opera-3D)

Thruster Simulations in Opera-3D:

- ‘Simplified geometry’ with single coil constructed in Opera-3D
- Modeling options: user interface, script language, or CAD file
- Original CAD model did not mesh well (result in poor solution)
- Converted CAD model into a script input file





Model – FEM (Opera-3D)

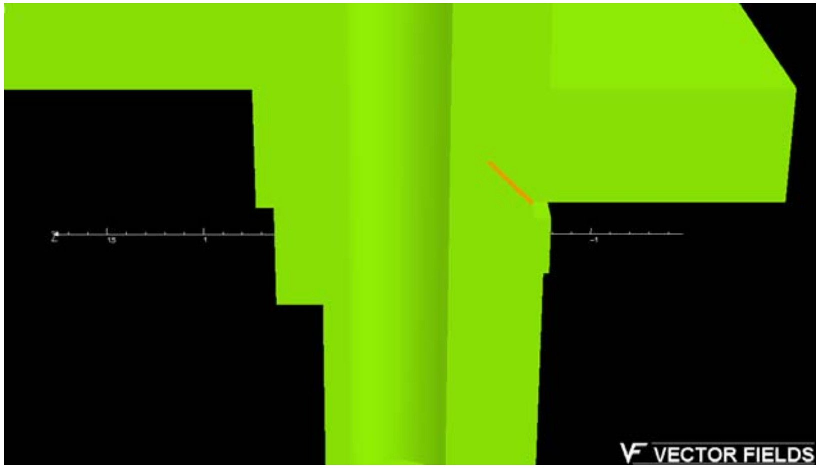
Thruster Simulations in Opera-3D:

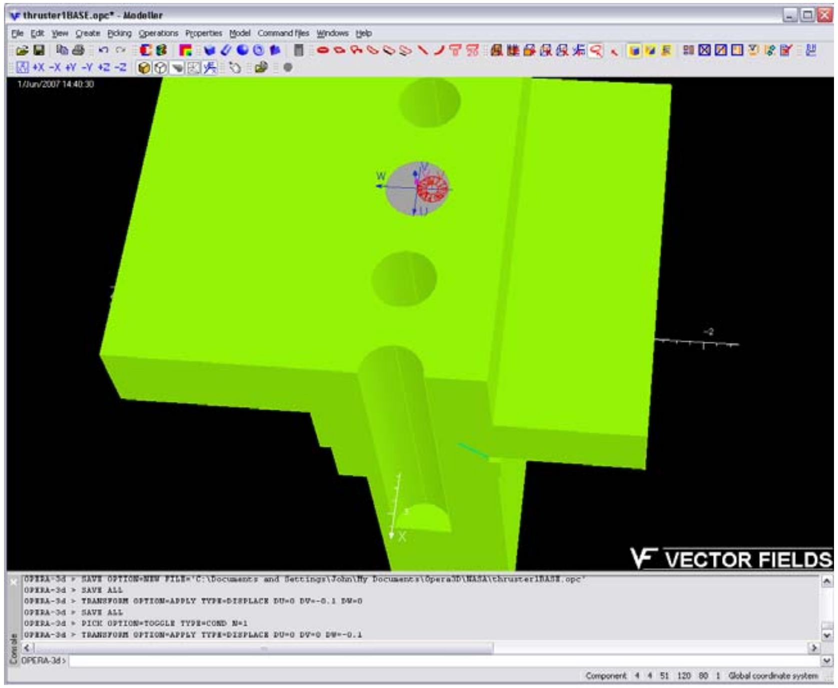
- Script file also required for running parametric studies
  - crack length
  - probe location
  - probe orientation
- Impedance from dissipated energy by the conductor (P) and stored energy (W) in domain

$$Z = R + j\omega L$$

$$R = \frac{P}{I^2} \qquad L = \frac{2W}{I^2}$$

$$P = \int J^e E^* d\Gamma' \qquad W = \frac{1}{2}\int H B^* d\Gamma$$





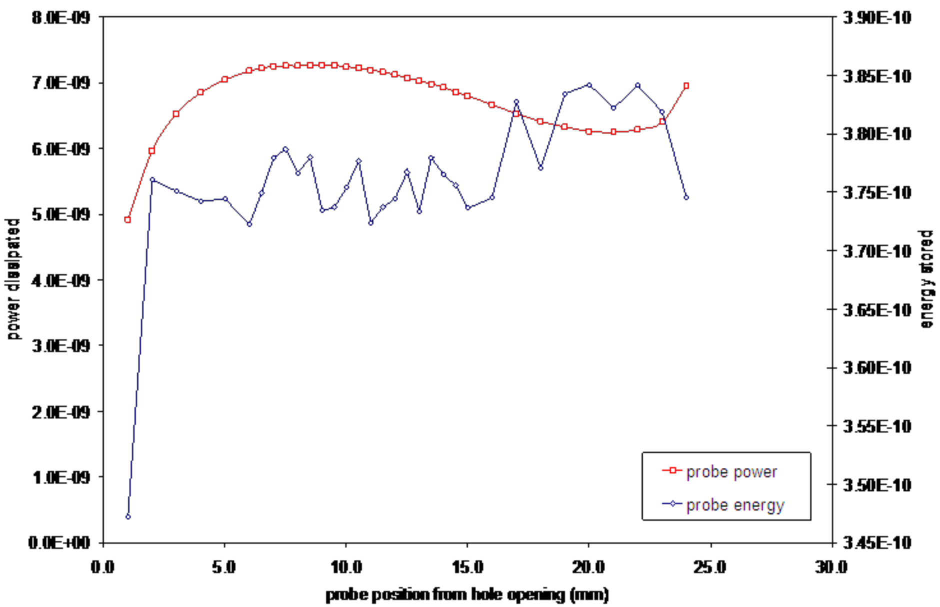
Results – FEM (Opera-3D)

Thruster Simulation Results in Opera-3D :

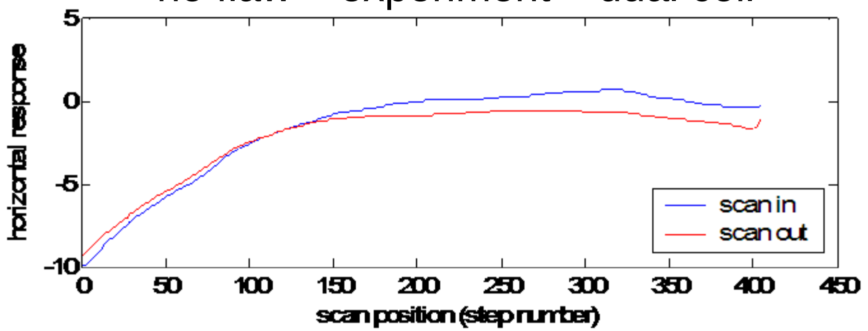
Absolute FEM results

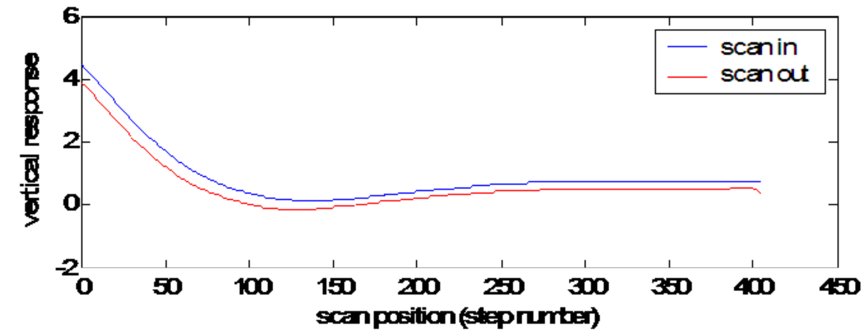
- *Irregular tetrahedral mesh* produces significant variation for probe at varying locations
- Trends observed in response assoc. with part geometry
- Increasing mesh density significantly increases solution time

no flaw – FEM simulation – tang(2) coil



no flaw – experiment – dual coil



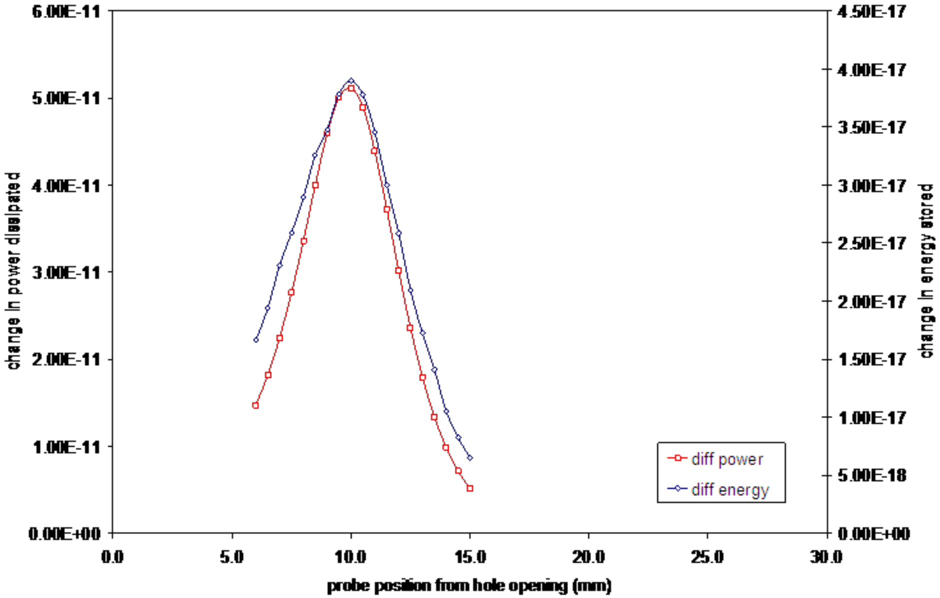


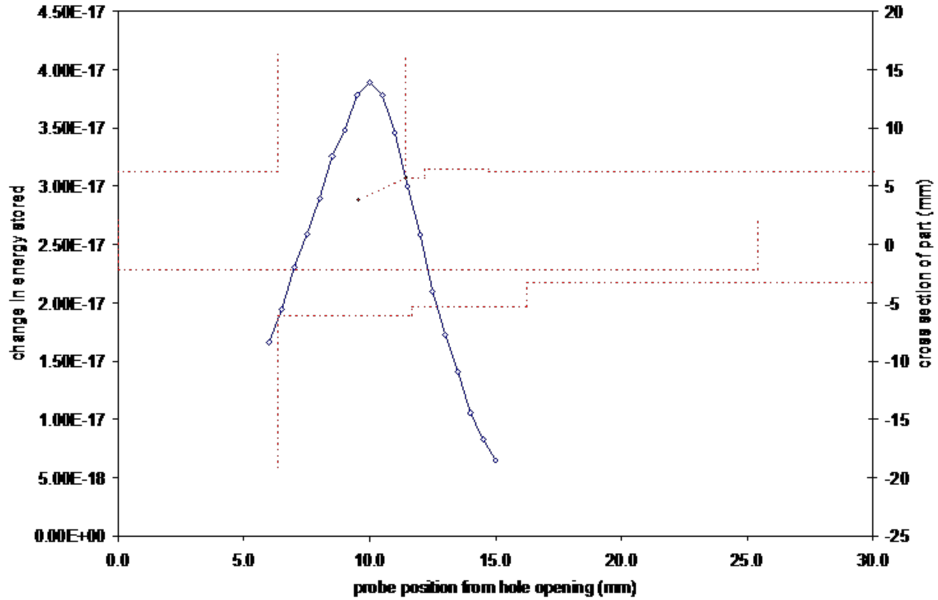
Results – FEM (Opera-3D)

Thruster Simulation Results in Opera-3D :

Differential FEM results

- Mesh variation error can be simply addressed by solving for both ‘no flaw’ and ‘with flaw’ conditions and taking difference
- Localized response
- Simulation time (two conditions * 26 probe locations): ~36 hrs



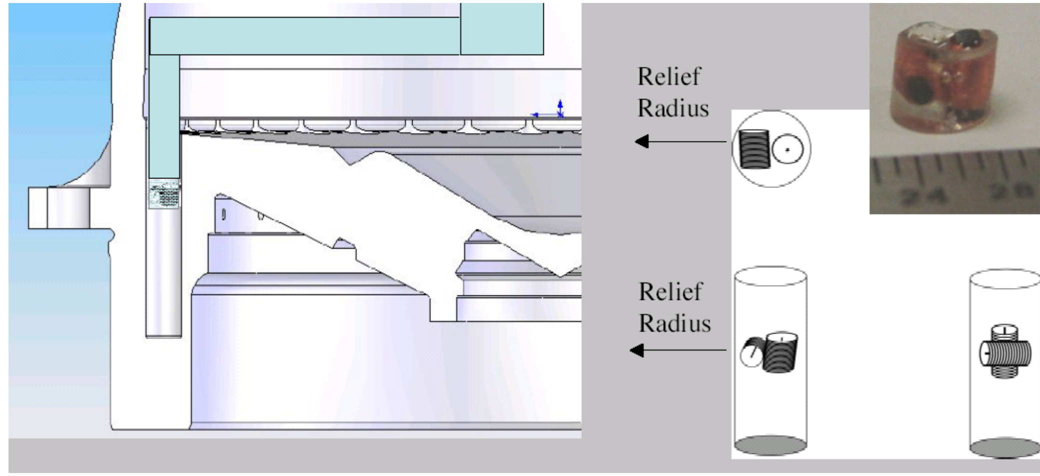


4. D. C. Carpenter, ‘Use of the finite element method in simulation and visualization of electromagnetic nondestructive testing applications,’ Materials Evaluation, Vol. 58, No.7, pp. 877-881, 2000

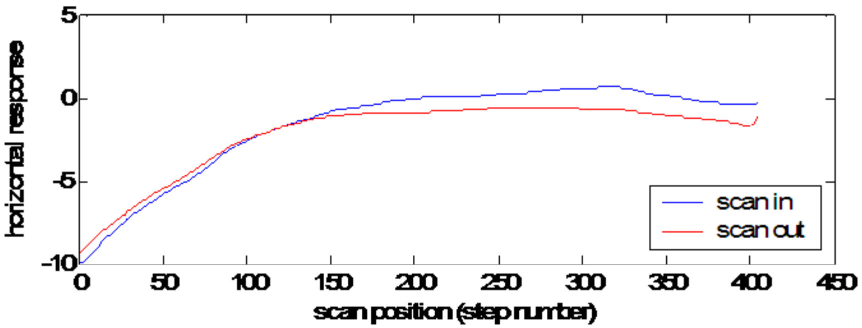
Comparison with Experiment

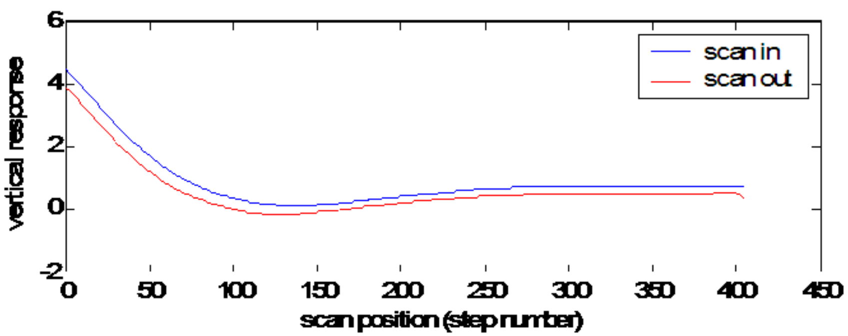
Experimental Results:

- Orthogonal probe
- 12 kHz

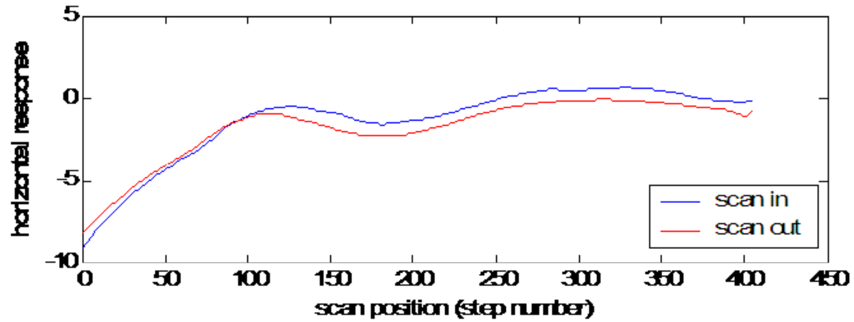


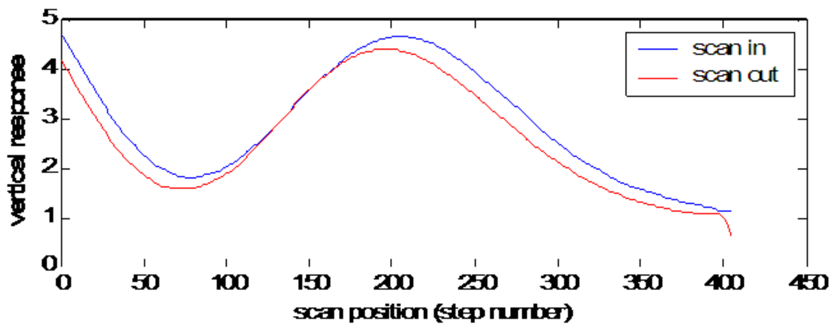
no flaw





with flaw (0.5 mm remaining wall thickness)





Volume Integral Method Formulation

- Start with Maxwell's equations

$$\nabla \times \mathbf{E} = -j\omega\mathbf{B}$$

$$\nabla \times \mathbf{H} = -j\omega\mathbf{D} + \mathbf{J}^{(e)}$$

- Restrict anomalous (flaw) regions to a layer
  (can address layers using spatial decomposition algorithms)

- Form system of volume integral equation's using Galerkin's method

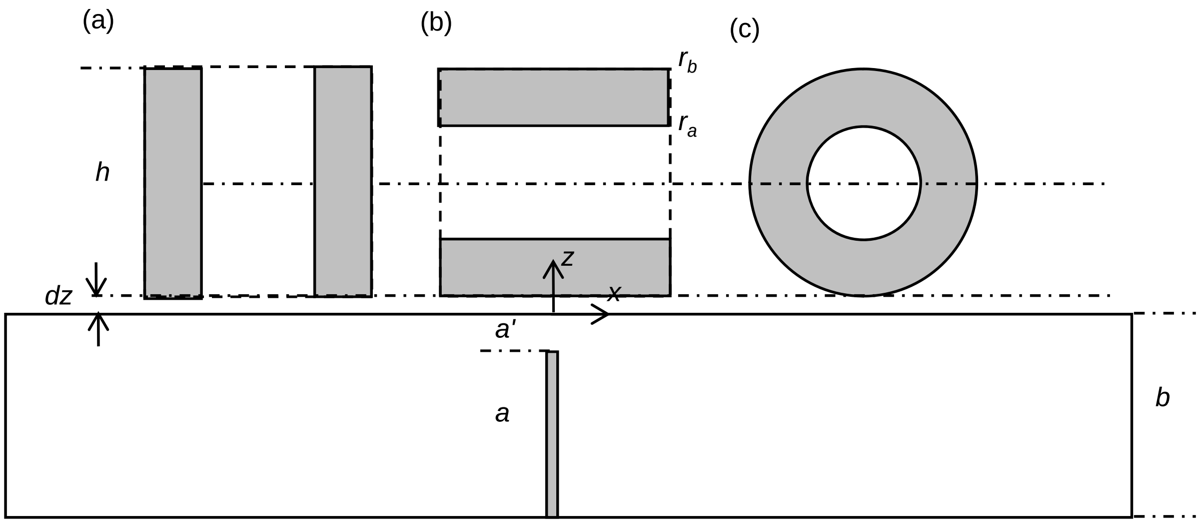
- Solve system of equations to evaluate scattering (anomalous) currents in the flaw region (Given incident field due to excitation coil)

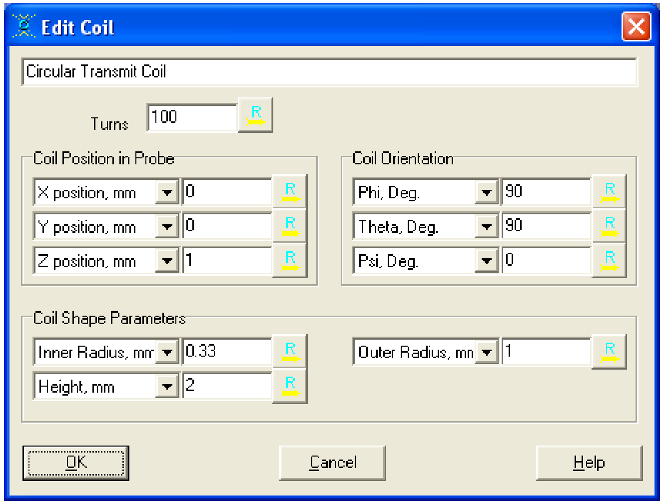
- Due to the Toplitz-Hankel structure of the equations, a 3D-FFT conjugate gradient algorithm can be used to solve large problems.

5. H. A. Sabbagh and L. D. Sabbagh, 'An Eddy-Current Model for Three-Dimensional Inversion,' IEEE Trans. Magnetics, Vol. MAG-22, No. 4, July 1986, pp. 282-291.

Model – VIC-3D

- GUI interface for def. of workspace (layers), probe and flaw region
  + All parameters can be selected for ranging
  – Cannot import complex geometry
- Only discretization of flaw region (open crack) required
- Localized defect simulations can be run in seconds
- First study: Use approximate model used to test probe orientation at multiple frequencies





coil GUI: case (c)

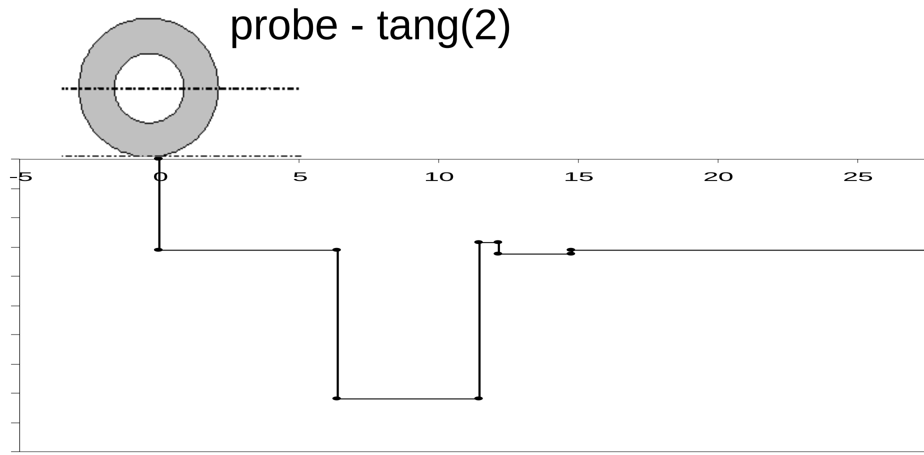
Simulated Response to Structure

Noise Distribution:

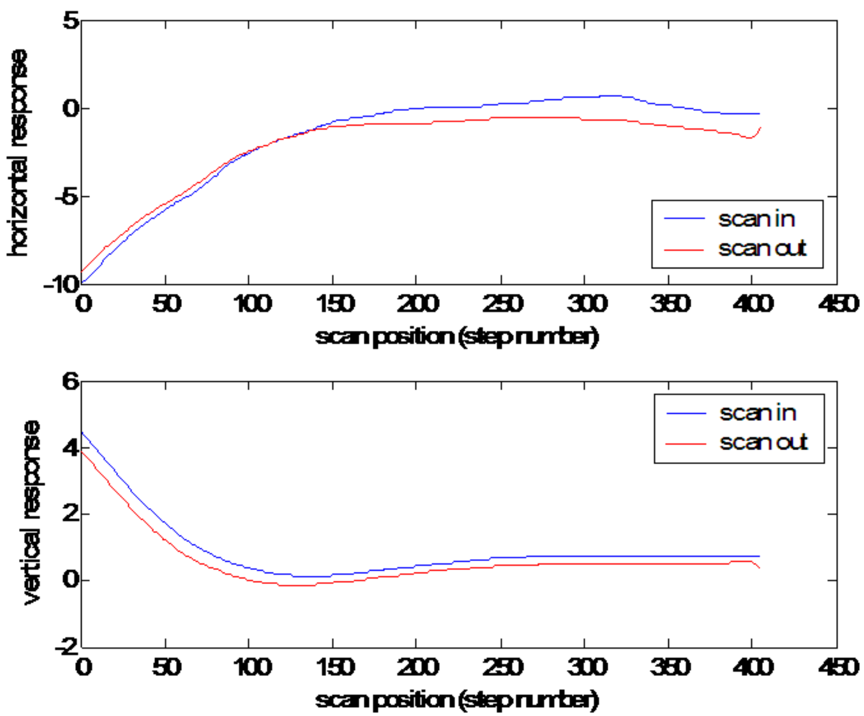
- **Variation due to structure**

Model Trends Match Experiment:

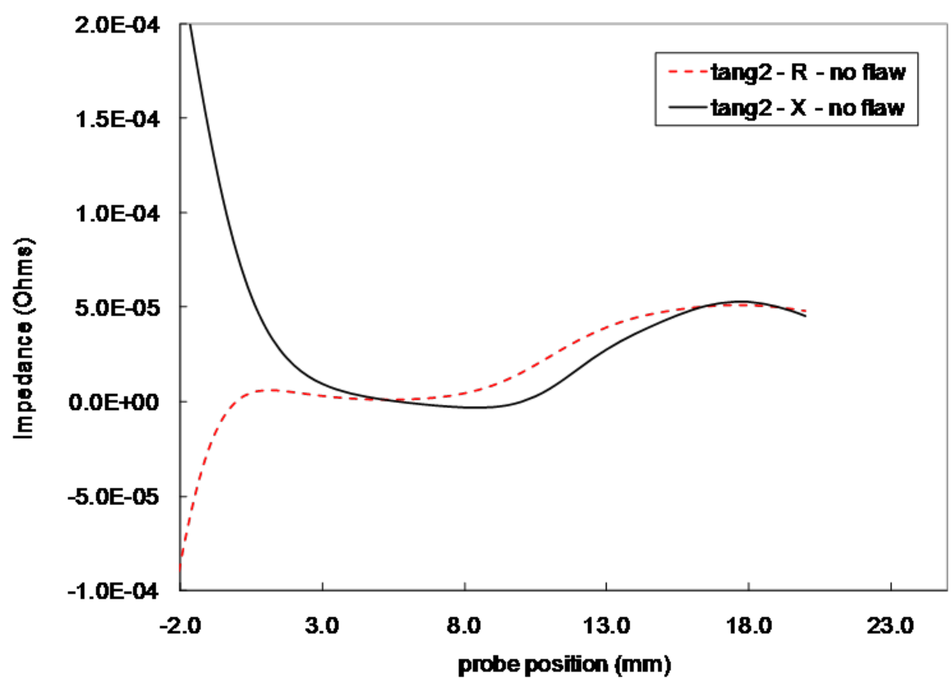
- **12 KHz data**



no flaw – experiment – dual coil



no flaw – model - tangential probe (2)

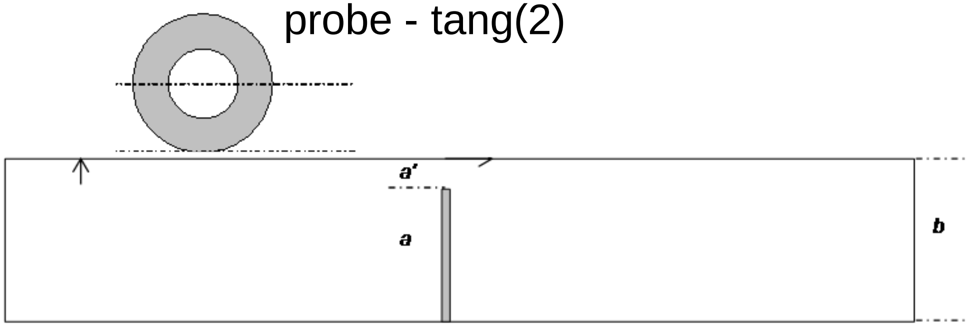


Response to Crack

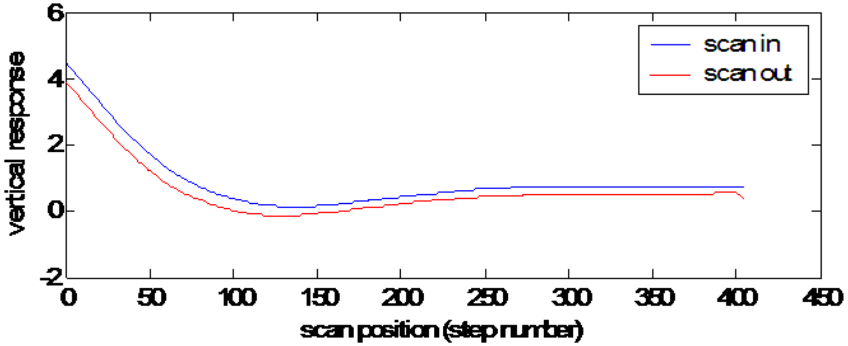
Crack Signal Distribution:

- **Function of crack size**
- **Compare experiment and simulation**

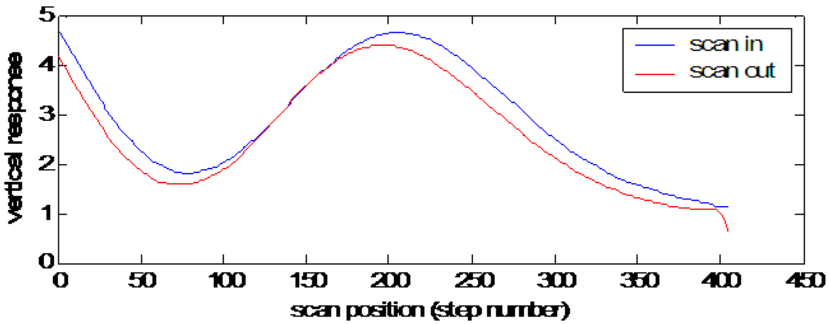
probe - tang(2)



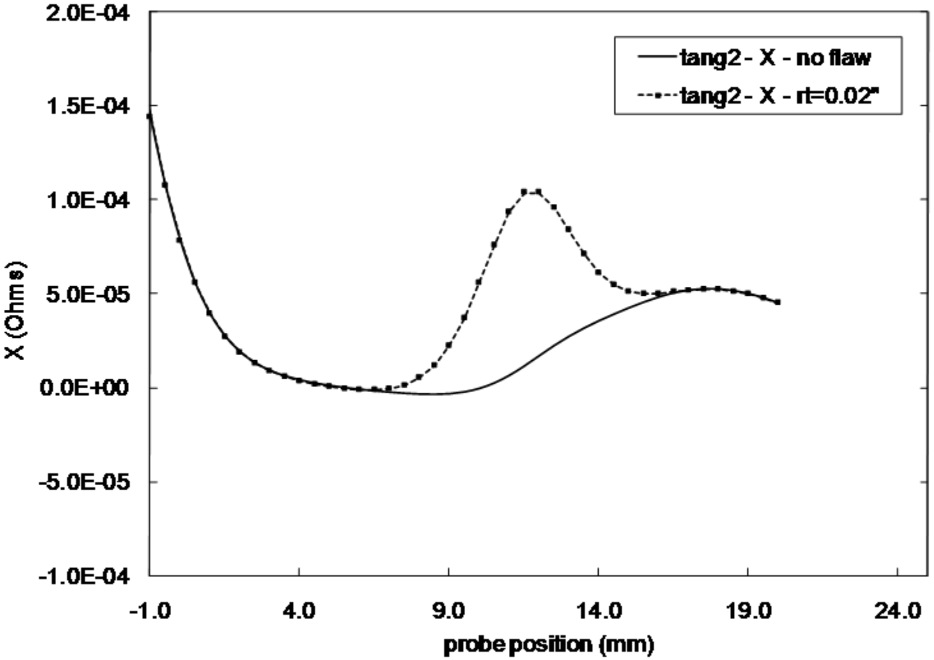
no flaw – experiment – dual coil



with flaw (0.5 mm remaining wall thickness)



with flaw (0.5 mm remaining thickness) – model - tangential probe (2)

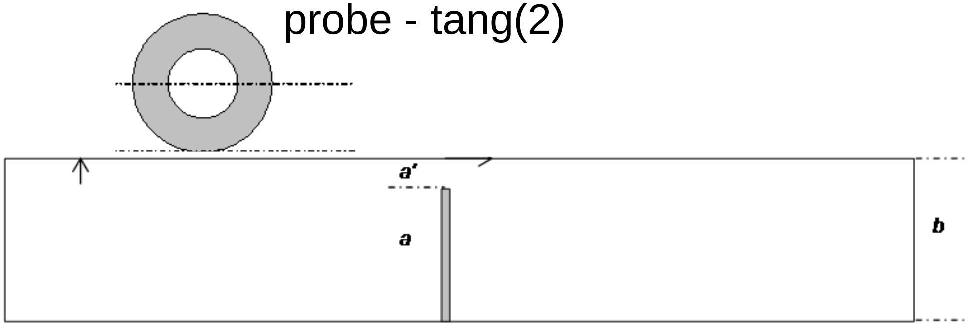


Sensitivity to Crack

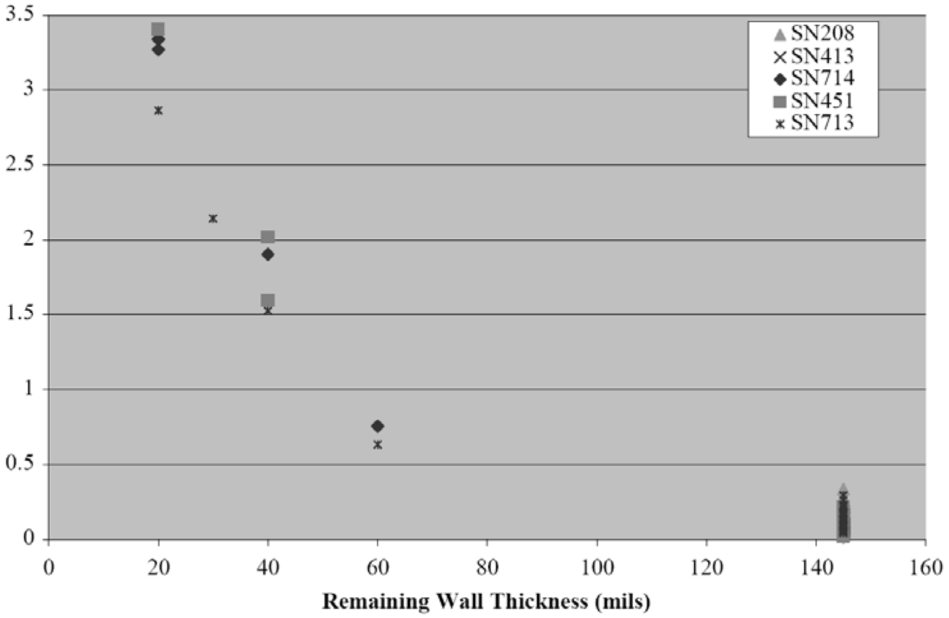
Crack Signal Distribution:

- **Function of crack size**
- **Compare experiment and simulation**

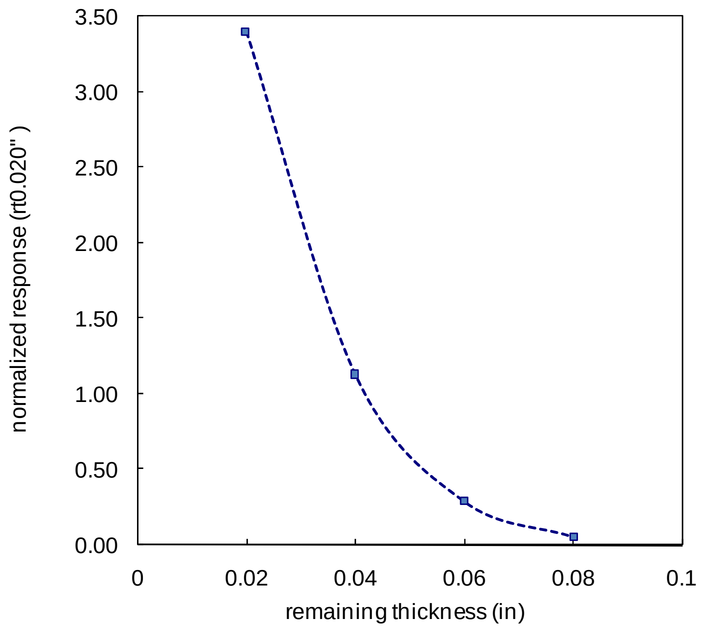
probe - tang(2)



vary remaining wall thickness experiments – dual coil [6]



with notch – model - tangential probe (2)

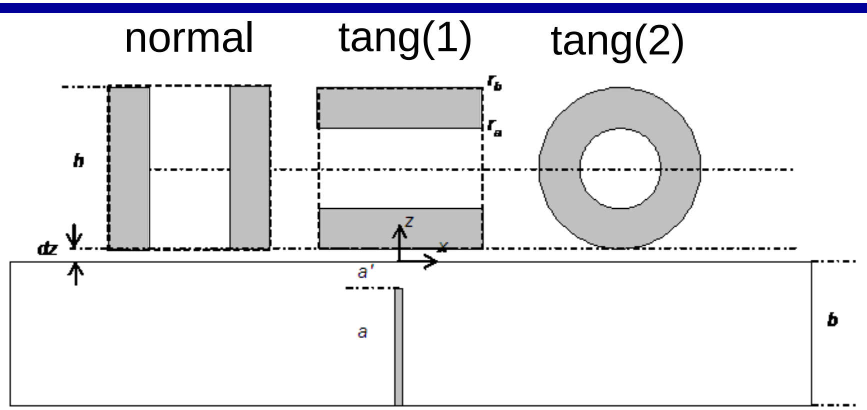


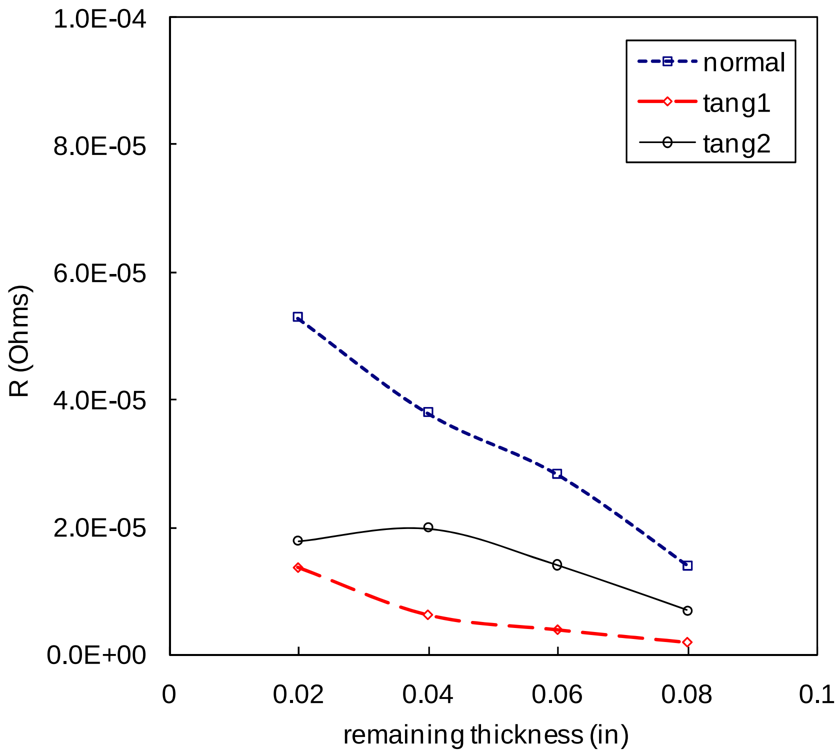
6. B. Wincheski, J. Simpson, A. Koshti, "Development of Eddy Current Techniques for the Detection of Cracking In Space Shuttle Primary Reaction Control Thrusters" NASA/TP-2007-21487.

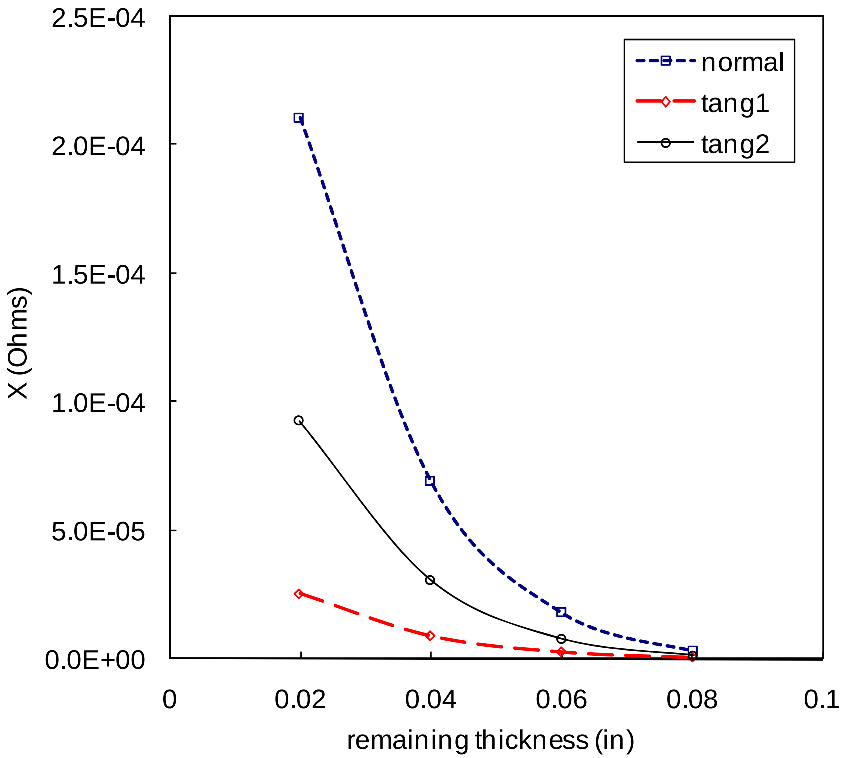
Sensitivity to Crack

Crack Signal Distribution:

- **Function of crack size**
- **Vary orientation and remaining thickness**

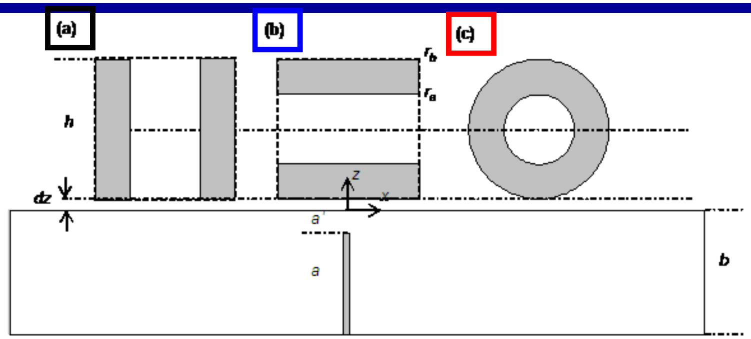




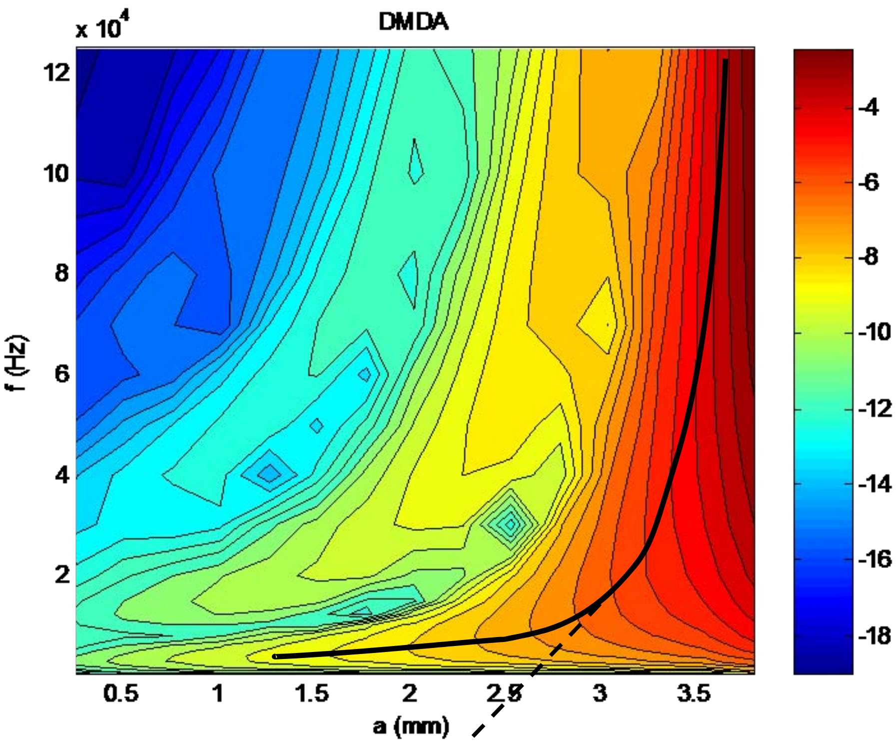


Sensitivity Analysis – VIC-3D

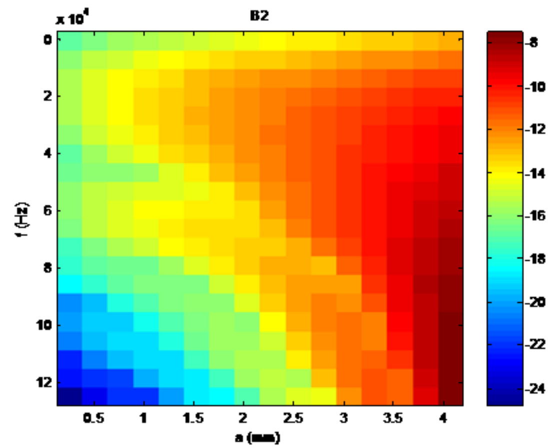
- **Evaluate measurement sensitivity as function of frequency and notch length**



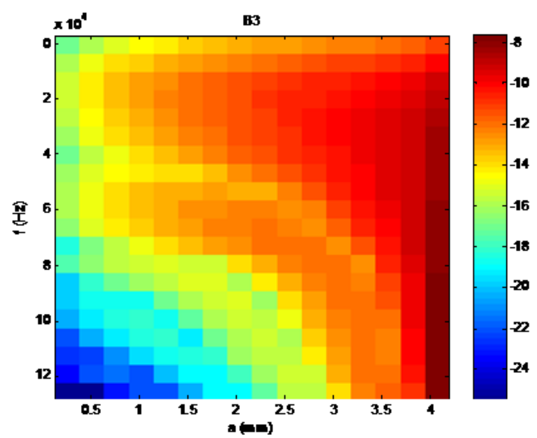
$$\frac{\partial Z(f,a)}{\partial a} \approx \frac{Z(f,a+\Delta a)-Z(f,a)}{\Delta a}$$



(a)



(b)

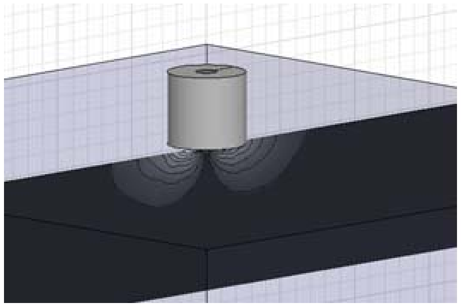


(c)

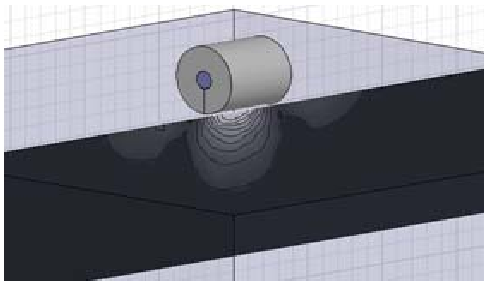
Metric for best frequency to perform sizing

Making Quantitative Comparisons

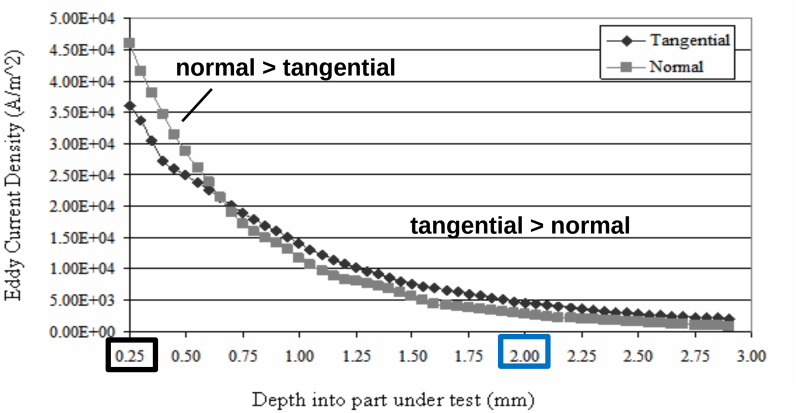
- **Prior Work – FEM of eddy current density (Wincheski et al. 2007)**



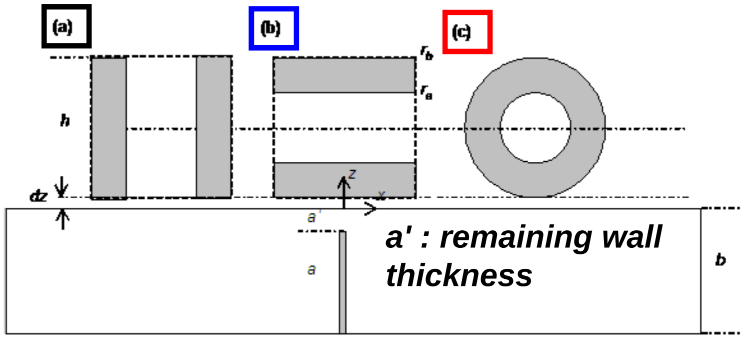
normal

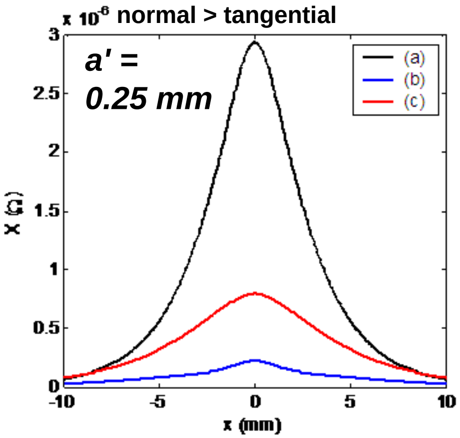


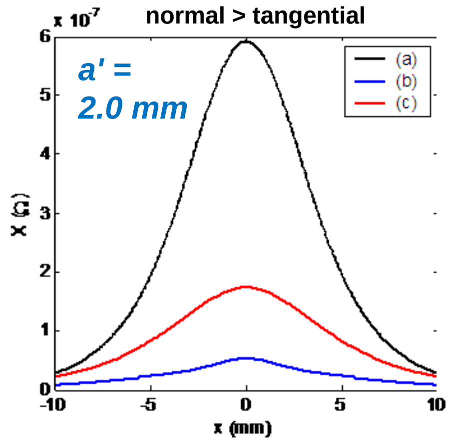
tangential



- **VIC-3D: EC measurement is due to 1) magnitude of eddy current density in flaw region and 2) measurement model of disturbed currents**



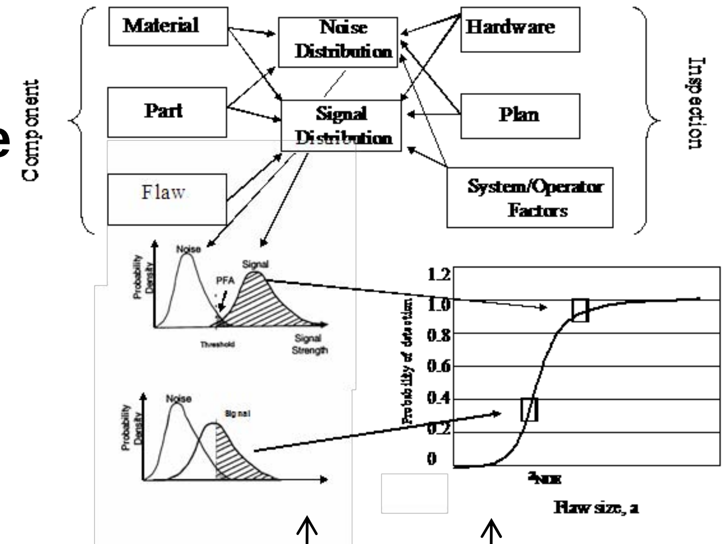




- **To make an accurate comparison between designs, there is need to also *include all associated variances (noise factors)* in measurements**

Model-assisted POD Protocol (Thompson et al)

1. Identify the scope of the POD study
2. Identify factors that control signal and noise
3. Evaluate quality of physics-based models
4. Acquire / develop / validate simulation tools



5. Acquire input parameters / parameter distributions
6. Conduct flaw signal distribution simulations and noise signal distribution simulations
7. Acquire remaining information on factors empirically
8. Acquire marginal information on independent factors and covariance information on dependent factors

9. Evaluate *full signal* and *noise distributions [f(crack length)]*

10. Compute POD with Probability of False Call (POFC) [Monte Carlo]

Model-assisted POD Protocol

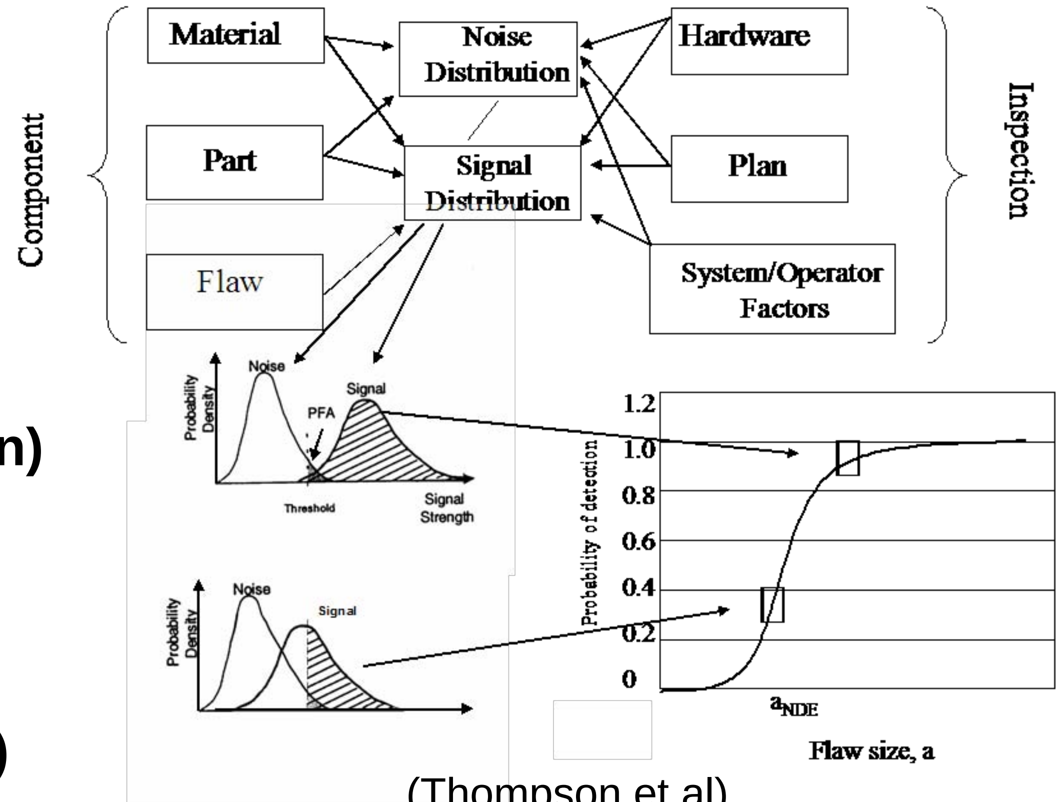
Noise Distribution:

- Variation due to **measurement** (*reference, self calibration*)
- Variation due to **structure**
- Variation due to **probe**
  - orientation (angular)
  - liftoff from surface

Crack Signal Distribution:

- **Function of crack size** (mean)
- Variation due to **crack geometry** (+ *probe*)
  - initiation site
  - crack orientation (angle)

\+ Include noise distribution



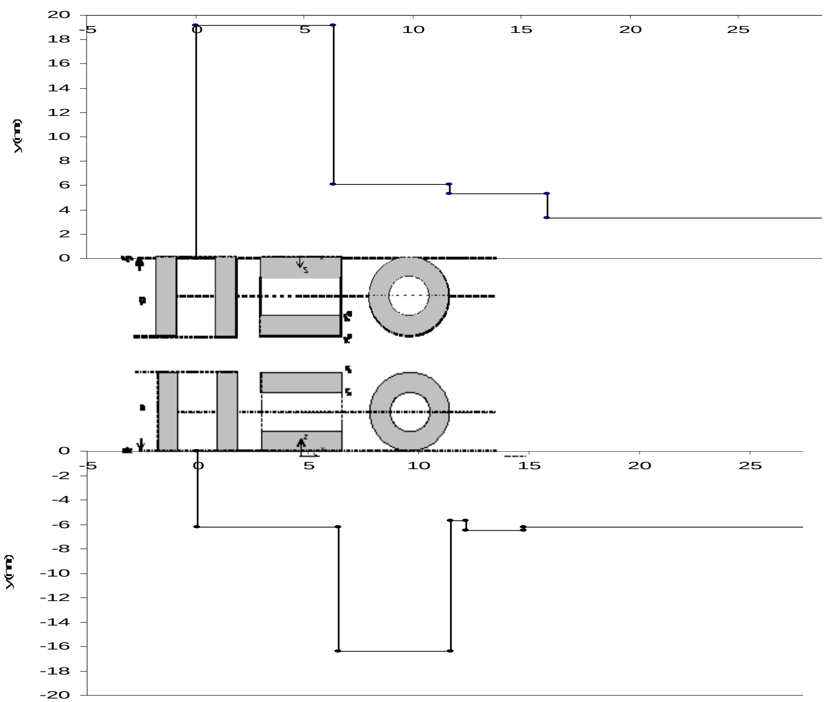
(Thompson et al)

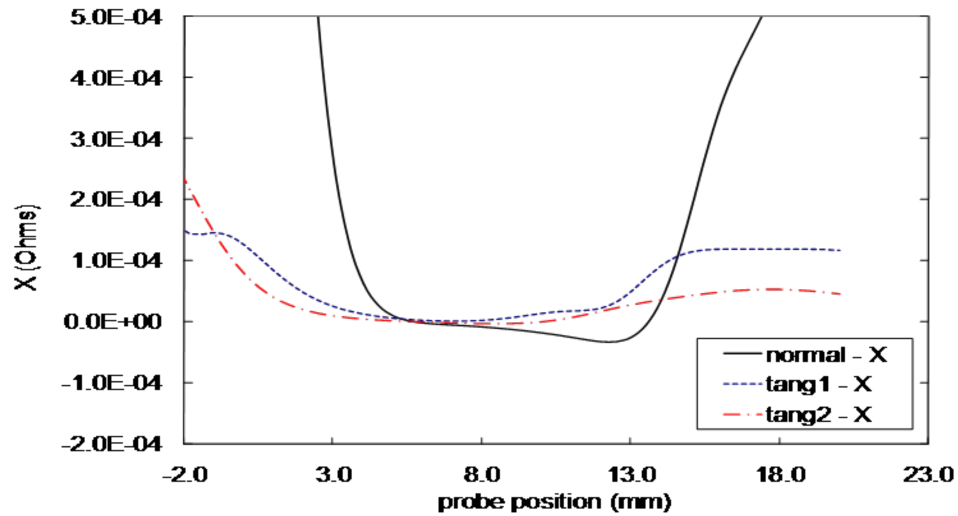
Sensitivity to Structure

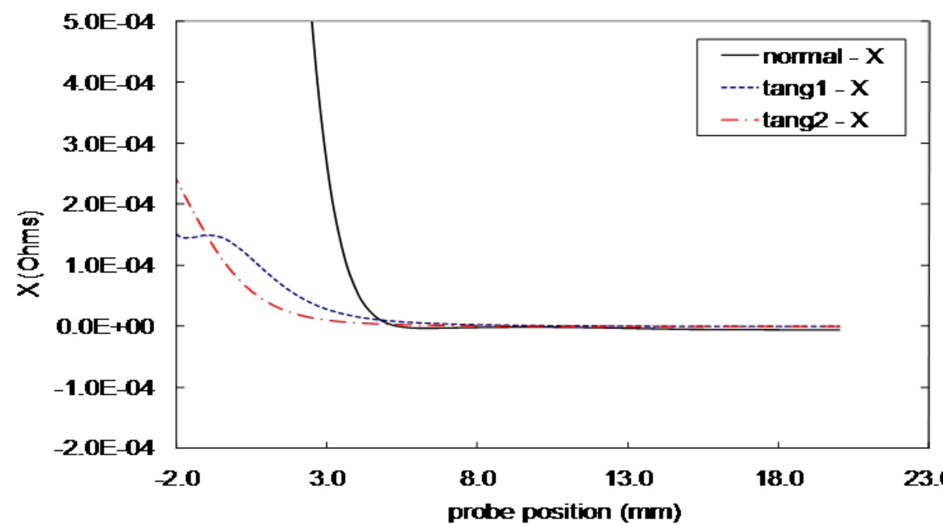
Noise Distribution: Variation due to structure

Use Approximate Model - *VIC-3D simulations (12 kHz)*

- *Split model into two parts (each half of structure)*
- *Evaluate sensitivity of probe orientation to structure*







Summary and Future Work

Summary:

- Two numerical methods, FEM and VIM, were used to simulate eddy current NDE for cracks in a complex thruster geometry
- Model demonstrated trends observed in experimental studies
- Sensitivity studies performed to determine the ideal probe orientations and frequencies for varying crack lengths.
- To make an *accurate comparison between designs* using simulation:
  - Need accurate measurement models
  - Must include all critical variances in measurements
- MAPOD study outlined with preliminary design results

Future Work:

- Complete full model-assisted POD (MAPOD) evaluation
- Explore hybrid models to efficiently solve for multiscale geometries
- Investigate optimum designs for improving detection of deep cracks

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